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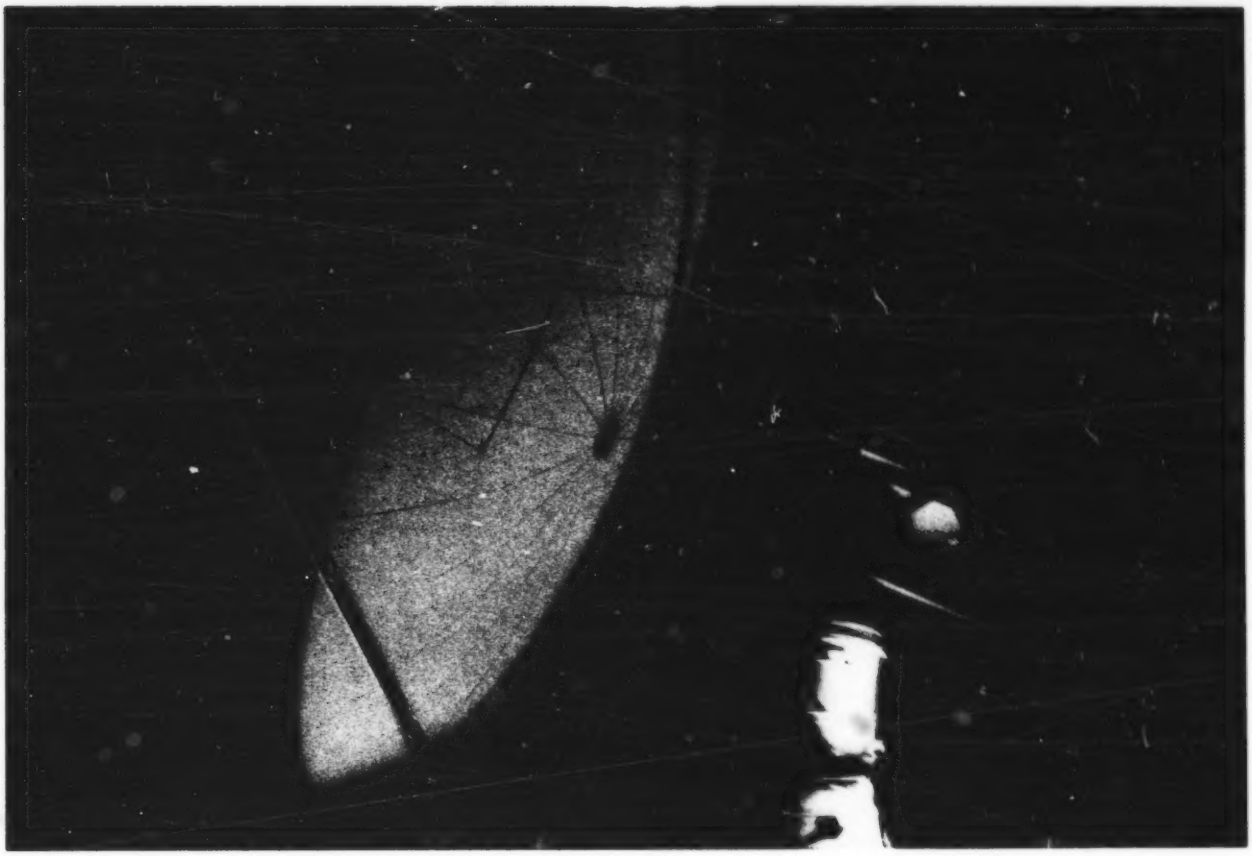
Radar for rainstorm intensity-duration estimates in central Alberta

L. Wojtiw



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ATMOSPHERIC SCIENCES DEPARTMENT, ALBERTA RESEARCH COUNCIL
EDMONTON, ALBERTA, CANADA 1986

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Abstract

Rainstorms which exceed the recommended design frequency of conveyance systems, and cause extensive damage to structures and property, occur frequently in Alberta. After such a severe storm, an early and quick assessment of the storm's location, magnitude, and frequency for various durations is often required to determine the damage. The storm intensity-duration curve is usually compared with the long-term intensity-duration curve of a selected frequency from the nearest recording raingauge to determine if the frequency of the event has been exceeded for any of the assessed durations. The storm intensity-duration curve is produced on information obtained from a sparse network of recording tipping-bucket raingauges, thus creating a high degree of uncertainty in the result. Short-duration precipitation is usually quite variable in Alberta; hence, a very dense network of recording precipitation stations would be required to provide accurate measurements of the storm intensity-duration curve at all locations. Such a dense network does not exist in Alberta, and one would be very expensive to install and maintain.

One solution for obtaining a large amount of closely spaced intensity-duration values is to use weather radar. Radar can be used to delineate the intensity of rainfall for various durations over large areas, thus becoming a very useful hydrometeorological instrument. The Atmospheric Sciences Department (ASD) of the Alberta Research Council has a radar that routinely obtains precipitation measurements that can be used to obtain storm intensity-duration curves for any location within 150 km of the Red Deer radar site. Using the radar data, intensity-duration curves could be produced routinely for a set of pre-specified locations. The radar data thus permit identification of the frequency of rainfall events quickly, cheaply, and accurately. As a pilot project to demonstrate the feasibility of the method and the potential of radar data, computer software was developed to derive, from archived radar data, intensity-duration values for up to a 2,500 km² area for a given storm. The values are presented as a series of contoured maps showing the distribution of maximum precipitation depths for each of the durations used to compute the intensity-duration curves. To demonstrate the computer software, maps of intensity-duration values for three storms occurring between 1982 and 1984 are presented in this report. An empirical Z-R relationship was also developed specifically for Alberta rainstorms and tested in a limited number of cases.

Introduction

Rainstorms with maximum depths of 50 mm or more occur frequently in Alberta, averaging about 11 occurrences per year (Vershuren and Wojtiw, 1980). Some of these storms exceed the recommended design frequency of conveyance systems and cause extensive damage to structures and property. After such a severe storm, an early and quick assessment of the storm's location, magnitude, and frequency for various durations is often required.

The procedure for evaluating the frequency of rainstorm occurrence is to determine the maximum precipitation depth for each of several durations ranging from 5 minutes to 24 hours. The resulting curve of the maximum rates of precipitation for the various durations is called a *storm intensity-duration curve.* This curve is then compared with the intensity-duration curve of a selected frequency of the nearest recording raingauge to determine if the frequency of the event has been exceeded for any of the assessed durations. Intensity-duration frequency curves are produced and are available from Atmospheric Environment Service (AES). The storm intensity-duration curve is produced on information obtained from a network of recording tipping-bucket raingauges, which record the depth of rainfall at 1-minute intervals (with data commonly extracted in 5-minute intervals). However, there are few recording raingauges in Alberta—only 54, or one gauge per 22,000 km². This results in less-accurate data, as daily readings from the nonrecording standard raingauge network must be used to interpolate rainfall measurements for various time intervals.

Short-duration precipitation is usually quite variable in Alberta; hence, a very dense network of recording precipitation stations would be required to provide accurate measurements to determine the storm intensity-duration curve at all locations. Such a dense network does not exist in Alberta and would be very expensive to install and maintain.

Potential of weather radar

One solution for obtaining a large amount of closely spaced intensity-duration values is to use weather radar. This is not a new technology, but one that is being used increasingly by developed countries for solving hydrological problems. Radar can be used to delineate the intensity of rainfall for various durations over large areas, thus becoming a very useful hydrometeorological instrument. Weather radar can complement or replace traditional rainfall sensors. With the greater sampling frequency (3 minutes or less) and greater sampling density (roughly one value per square kilometre) offered by radar, a more complete description of rainfall events can be produced.

The Atmospheric Sciences Department (ASD) of the Alberta Research Council has a radar that routinely obtains the precipitation measurements described above. The department has also collected vast amounts of recorded data from past rainstorms. (Over 4000 computer tapes have been collected since 1975.) From the rainfall measurements obtained throughout the summer months by weather radars operated by the Alberta Research Council, it is possible to generate intensity-duration curves for any location within 150 km of the radar site, which is located 10 km southwest of Red Deer. This is equivalent to obtaining rainfall information in an area extending from Edmonton in the north to Calgary in the south, and Coronation in the east to Brazeau in the west.

Using the radar data, intensity-duration curves could be produced routinely for a set of pre-specified locations. They could also be produced on request from ar-

chived data for specific days and locations. Thus, from the radar data, the potential exists to identify the frequency of rainfall events quickly, cheaply, and accurately.

Proposed computer software development

An obstacle to the production of intensity-duration curves using radar is the lack of necessary computer software. As a pilot project to demonstrate the feasibility of the method and the potential of radar data, computer software was developed to derive intensity-duration values for up to a 2500 km² area for a given storm, from archived radar data. The values are presented as a series of contoured maps showing the distribution of maximum precipitation depth for each of the durations used to compute the intensity-duration curves. To demonstrate the computer software, maps of intensity-duration values for three storms occurring between 1982 and 1984 are presented in this report. Before the software package is presented, interpretation of rainfall measurements from raingauges and radar is discussed to provide the reader with background on these topics.

Precipitation data from raingauges

Intensity-duration curves

The intensity-duration graph (also known as the Yarnell (1935) frequency graph) can be constructed from frequency analysis of short-duration point rainfall values. The construction of this graph can be found in any standard hydrology textbook, thus it is not presented here. On such graphs, rainfall intensity is usually displayed for durations of 5 minutes to 24 hours, with curves drawn for the various return periods of 2 to 100 years. The intensity-duration curves are produced from available data by the national weather service (AES in Canada). An example of an intensity-duration graph for the Edmonton Municipal Airport in Alberta is shown in figure 1. This type of graph represents the climatological frequency of occurrences of rainfall rate in a given location. For a given duration the user can then determine the intensity or amount for a desired return period. For example, for a 30-minute duration the rainfall rate for a 25-year return period at the Edmonton Municipal Airport is 65 mm per hour, or a 30-minute accumulation of about 32.5 mm of rainfall. Hence, if a rainstorm produced more than 32.5 mm in any 30 consecutive minutes during its lifetime, this storm would be regarded as having exceeded the 1-in-25 year event. In addition to the graphic representation of intensity-duration shown in figure 1, AES makes available tabular listings of the amount of rainfall for various return periods together with the 50 percent confidence limits. Two main criteria necessary for obtaining intensity-duration information are: (1) the rainfall data should be collected on a short time scale (a 1-minute time interval is commonly used); and (2) the data should be collected over many years. The first criterion eliminates a large number of rainfall observations in this province from being used for this purpose, since they are recorded hourly (for example, at 6, 12, or 24 hours), rather than in minutes.

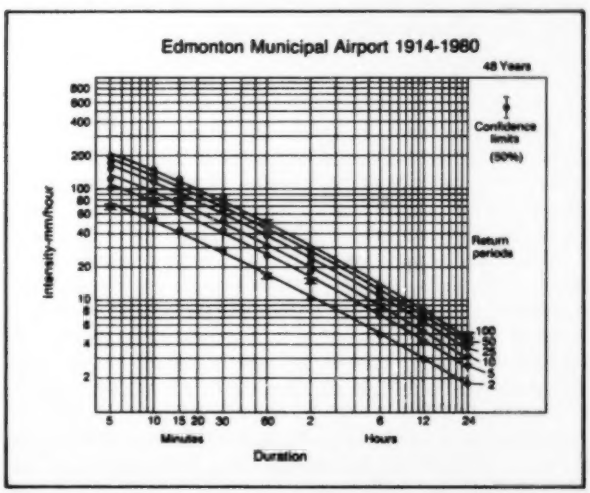

Figure 1. Intensity-duration graph for the Edmonton Municipal Airport. Note that the quantities are plotted on logarithmic scales (unreferenced AES publication).

The second criterion is also important, because the record period has been identified to affect the confidence that can be placed in the interpretation of the rainfall information. The longer the record period, the lower the variance and the 50 percent confidence limits, hence the greater the reliability of the results. Based on studies by Hershfield (1961), about 50 years of data can be regarded as the standard, and this number is needed to provide a stable data set. Stations with period of records below this standard have an error (or a large variance) associated with the statistics of the annual series. Hershfield's work suggests that about a 30 percent error exists in the standard deviation, and a 5 percent error in the mean, if the station has only 10 years of available data. In Alberta, the rainfall intensity data from the AES stations have lengths of record ranging from 10 to 49 years. Most of these stations are far below the standard of 50 years advocated by Hershfield. When using these data, it needs to be remembered that the return period values may have an error associated with them; because of the short record lengths, these values should not be regarded as absolute.

The spatial distributions of the 1-in-25 year rainfall events for Alberta can be generated from available AES data for intensity-duration analysis for periods of 5 minutes to 24 hours. These maps provide the reader with a quick reference to probable rainfall amounts at

locations where no raingauges exist, and show how the intensity-duration values vary spatially within the province.

Representation of point rainfall observations

The data used in the intensity-duration analysis are collected by a tipping-bucket raingauge which has about a 325-cm² catchment area. These point values are frequently assumed to be representative of a 65 km² (25 mi²) area. Conversion of point values to areal measurements for rainfall has been examined by various authors (Court, 1961; Hershfield, 1961; McKay, 1965). It is generally accepted that, for steady rainfall over many hours, point measurements can be extrapolated to a 65 km² area without an error. However, for thunderstorms, where heavy, short-duration rainfall can occur, assigning a 65 km² area to a point value is questionable. In fact, for some storms, it is uncertain that the point observations can be considered to be representative of even an area as small as several square kilometres. In numerous cases, rainfall has been observed to produce large depths on one side of a farmer's field with very little rainfall across the road. Such observations are typical of the nature of rainfall phenomena in thunderstorms on the Canadian prairies. Without an extensive network, it is frequently very difficult to obtain a good representation of the rainfall. Hence, an adequate representation requires many closely spaced observations. To adequately estimate the rainfall measurements necessary for intensity-duration analysis, either a large network of tipping-bucket raingauges or some sort of remote sensing instrumentation is necessary.

Density of rainfall observations

Another concern that exists with intensity-duration rainfall measurements is the inadequate density of observations. Even assuming that a 65 km² area can be represented by a point measurement, to obtain sufficient information on rainstorms, hundreds of tipping-bucket raingauges would be needed to adequately cover a typical rainstorm in Alberta. Vershuren and Wojtiw (1980) showed that rainstorms in Alberta that produce a maximum depth of 50 mm or more cover areas of thousands of square kilometres. Few tipping-bucket raingauges exist in Alberta and about 50 percent of these are in Edmonton and Calgary. For much of the rural area, little or no information exists to determine if flooding may have occurred from severe rainstorms.

The importance of the rainfall observation densities can be illustrated by examining figures 2 to 5, where various densities of coverage are used for the 24-25 June 1983 rainstorm. Here, daily observations of surface rainfall were used from a network of 278 stations in a 23,460 km² area in central Alberta. This network was maintained by the Alberta Research Council for which volunteer observers measured and recorded daily rainfall amounts. In the above area, few

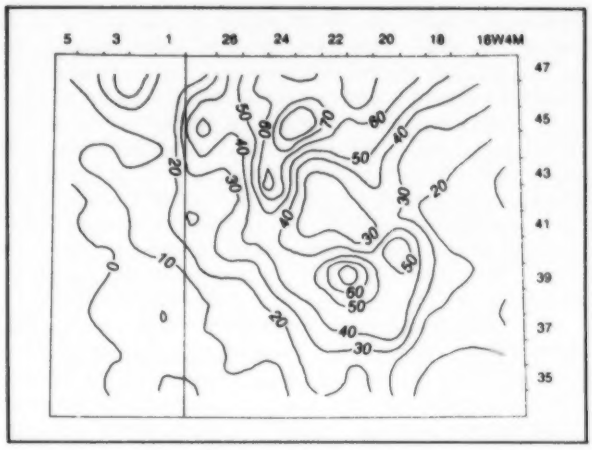

Figure 2. Isohyetal map (in mm) for the 24-25 June 1983 rainstorm using an average density of 1 gauge per 84 km².

measurements of short-duration rainfall exist from the Canadian national weather network. Computer simulations were performed on the observed rainfall amounts to determine what effect a network with fewer stations would produce. The data points were arbitrarily selected in the sense that every second observation was dropped in the progression from figure 2 to figure 5, while maintaining uniformity of observations in the resultant network. A computer software package, SURFACE II (Sampson, 1975), was used to produce the contours on the map to avoid human bias in contouring. (SURFACE II is a package capable of producing displays of spatially distributed data.) To illustrate the importance of the density of measurements, four figures are presented: (a) figure 2, where all the available daily rainfall amounts are used (equivalent to an average density of 1 gauge per 84 km²); (b) figure 3, where one-half of the rainfall observations were used (average density of 1 gauge per 169 km²); (c) figure 4,

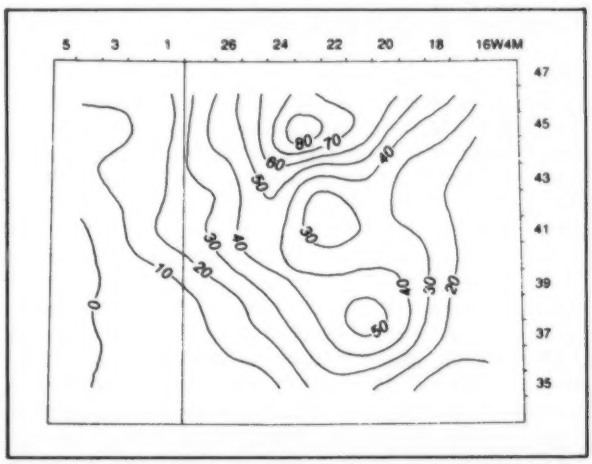

Figure 3. Isohyetal map (in mm) for the 24-25 June 1983 rainstorm using an average density of 1 gauge per 169 km².

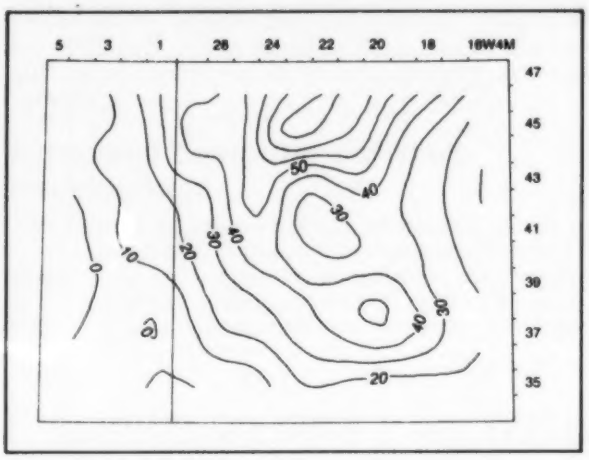

Figure 4. Isohyetal map (in mm) for the 24-25 June 1983 rainstorm using an average density of 1 gauge per 340 km².

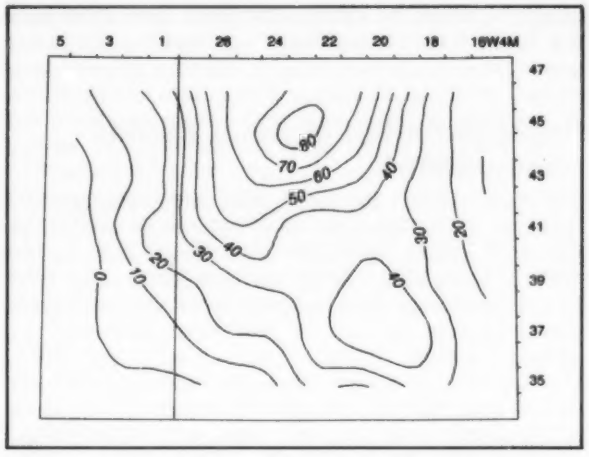

Figure 5. Isohyetal map (in mm) for the 24-25 June 1983 rainstorm using an average density of 1 gauge per 690 km².

where one-quarter of the observations are used (average density of 1 gauge per 340 km²); and (d) figure 5, where one-eighth of the observations are used (average density of 1 gauge per 690 km² — approximately the density of the nonrecording raingauge network for Alberta). By examining the four figures, it can be noted that with fewer observations the following things occur: (a) the isohyetal patterns become less refined, lacking the complex gradient structure observed for rainstorms; (b) the area covered by the rainstorm generally increases; and (c) the maximum value decreases from that recorded. The true maximum value in a rainstorm is unknown. In reality, most networks attempt to obtain values which approach the maximum or at least give the best available approximation to the maximum. How successful this approximation is depends on the density of available measurements.

For intensity-duration analysis in Alberta, the approximation can at best be described as crude, because so few observations exist. Establishing large networks of tipping-bucket raingauges is very costly and time consuming. Yet, greater resolution of rainfall rates and amounts is desired by engineers, hydrologists, meteorologists, and users of water resources. Hence, it is not surprising that a greater emphasis has now been directed to use remote sensing instrumentation to collect precipitation measurements. Radar is being more frequently used in hydrological applications to obtain many closely spaced, short-duration rainfall amounts.

Radar measurements and interpretation

"Radar" is an acronym used since World War II to describe the technique and equipment employed for the "Radio Detection And Ranging" of objects in the atmosphere. Radar detects and locates objects, just as a beam of light from a searchlight picks out an object in the dark. But radar does so both in daylight and darkness, through thick clouds and at greater distances than a beacon. Both processes work on the principle that a small part of the transmitted energy is reflected back towards the source after striking an object. Meteorologists use radar (known as weather radar) to detect, locate, and measure the amount of precipitation in clouds. The weather radar emits microwave energy in short bursts, focused in a narrow, conical beam which scans the atmosphere from a slowly rotating antenna. In most weather radars each energy pulse lasts only one or two millionths of a second, and the interval between pulses is about 2000 times as long (about four milliseconds). Radio frequencies for weather radars are in the band between 3,000 and 10,000 million cycles per second (megahertz) and have been selected to provide both maximum penetration through clouds and good reflection from precipitation particles.

The microwave beam transmitted by weather radar will pass through cloud and fog but, when it strikes precipitation particles, such as raindrops, snow flakes or hail, some of the energy is backscattered as an echo to the radar antenna. The amount of energy scattered back to the radar is related to the precipitation intensity. Since both the speed at which the microwaves travel (close to the speed of light) and the direction in which the antenna is pointing are known, the distance and direction of the precipitation from the radar transmitter can be determined from the radar echoes. This permits the mapping of precipitation over the area covered by the radar.

The backscattered energy or echo is picked up by

the antenna during the pause between energy pulses and is fed to a receiver, where it is amplified and transformed by computer into numeric information. This information can be saved on magnetic tapes (for later analysis) or displayed on a video-screen, where the shading varies with the different amounts and rates of precipitation.

Relationship between radar reflectivity and precipitation rate

Empirical studies indicate that a relationship exists between the radar reflectivity factor, Z, and precipitation intensity, R; hence radar can be used for estimating rainfall rate or amount. Some scientists have visualized that radars, which can detect rainfall over a very large area, ultimately will replace raingauges. Others have taken the position that radar should complement raingauges and, when used together, would provide significantly better information on the rainfall than can be obtained solely from a raingauge network. Various studies have been made to test the validity of the equation relating backscattered power to rainfall intensity. Direct observations of rainfall have been compared with calculations made from simultaneous radar observations. In general, the investigations have shown that properly calibrated radars can make reasonably accurate measurements of rainfall intensity and of accumulated rainfall over a small watershed. If radar characteristics are known, the Radar Equation (Probert-Jones, 1962) can be expressed as a relationship between Z and the precipitation rate (R), under certain assumptions. Assumptions include: the use of 10-cm radar; radar is detecting rain; and rain consists of spherical water drops small enough to permit the Rayleigh approximately to apply.

In order to use radar for measuring rainfall intensity, most investigators have used an empirical expression of the form

$$Z = AR^b \qquad (1)$$

where Z is in millimetres to the sixth power per cubic metre, A is a coefficient to be determined, R is in mm per hour, and b is an exponent to be determined. Battan (1973) provides a list of various relationships that have been reported in international literature. Although the equations listed in Battan differ markedly at small and large values of R, with the exception of curves for orographic rains, most of them do not differ greatly at rainfall intensities between about 20 and 200 mm per hour. The Marshall-Palmer (1948) relationship, $Z = 200\ R^{1.6}$, was developed in the early history of radar meteorology from Canadian data (in eastern Canada) collected in temperate zone rainfall that was usually stratiform in nature. In the past, it has been common when other information has been lacking to use this relationship for all types of rainfall. However, Battan suggests that this procedure is no longer appropriate.

The lack of sufficient data from tipping-bucket gauges within radar coverage has slowed progress in the development of a Z-R relationship for rainfall in Alberta. Usually a single rainstorm covers very few raingauges, thus making calibration difficult. Three Z-R relationships are investigated in this report to determine which relationship is best suited for Alberta rainstorms. The relationships investigated are: (1) the Marshall-Palmer (A = 200, b = 1.6), because it is regarded as the classical relationship; (2) the Hood (1950) (A = 295, b = 1.61), because this was developed for Canadian rainstorms; and (3) the Wojtiw (A = 168, b = 1.72), developed in this report for several Alberta rainstorms (including the 5 July 1984 storm).

The 5 July 1984 rainstorm passed through the city of Edmonton where 11 raingauges within ASD radar coverage were operated by Edmonton Water and Sanitation Department. This is one of the few storms that has occurred in Alberta for which a number of raingauge measurements are available to help calibrate a Z-R relationship. The resultant calibration graph for this storm, and what is believed to be a good relationship for Alberta rainstorms, is shown in figure 6. Here, the rainfall rate (vertical axis) was obtained from surface tipping-bucket data, and the reflectivity (horizontal axis) came from the S-band 10-cm radar near Red Deer.

The rainfall rate used here is the rainfall rate occurring in the 5 and 10-minute intervals of the lifetime of the rainstorm, and the reflectivity is the time-integrated average over the corresponding durations. The 5-minute rainfall amount was the minimum duration readily available in the tipping-bucket data. The reflectivity value (areal coverage of one value of radar data representing approximately about 1 km² area) in the bin closest to the surface measurement was selected for the comparison. The straight line shown in figure 6 is the best-fit equation, with coefficient A = 168 and b = 1.72 (in equation 1), and a correlation coefficient of 0.83.

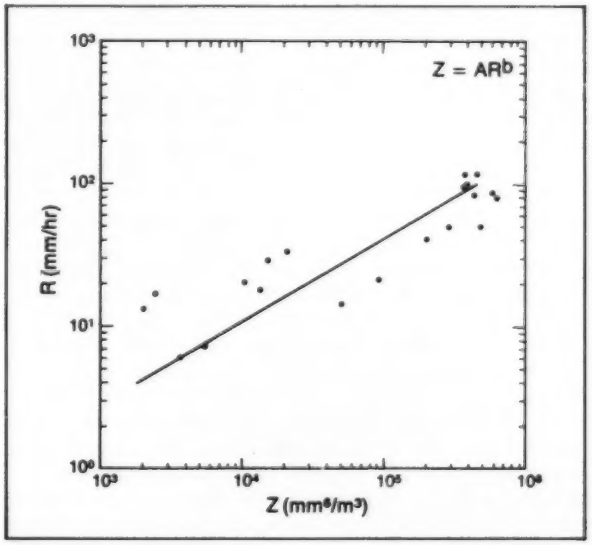

Figure 6. Z-R relationship developed for Alberta rainstorms.

From all indications, this Z-R relationship gives results which agree well with surface observations. This equation was tested for two other rainstorms yielding similar agreement to ground observations. The other two relationships (Marshall-Palmer and Hood) seem to give just slightly higher rainfall amounts overall, in each of the three storm cases.

Sensitivity of the parameters in the Z-R relationship

The sensitivity of the parameters in the Z-R relationship was also investigated. The results can be best summarized and depicted in figure 7. The percentage change in either parameter A or b (of equation 1) is shown versus the resultant percentage change in the rainfall amount.The results in figure 7 were computed from the 5 July 1984 rainstorm radar data using the Marshall-Palmer relationship. It is believed that the other two relationships (Hood and Wojtiw) would produce similar effects. Thus, these results are believed to be typical of the behavior and sensitivity of the Z-R relationship. The results show that a percentage decrease in parameter A produces an almost equal percentage increase in rainfall, and an increase in parameter A produces about half as much percentage decrease in rainfall. Thus, a change in parameter A has a moderate effect on the rainfall amount. although it is not believed to be significant. However, variation in the rainfall amount is extremely sensitive to variations in the exponent, b. A slight error in the exponent will result in a large error in the rainfall amount. However, experience shows that, when b increases, A tends to decrease, and vice versa, so they tend to balance each other out.

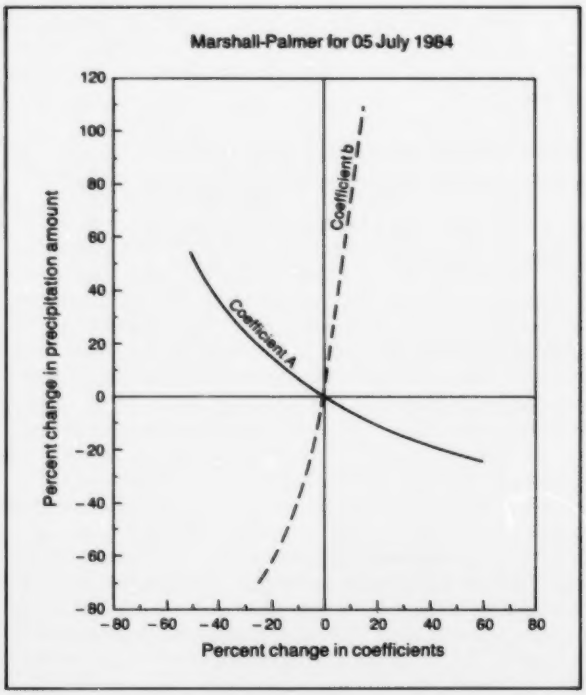

Figure 7. Sensitivity of the parameters A and b in the Z-R relationship, and the effect on rainfall amount.

Data management and computer software development

Weather radars and rainfall gauges can provide improved rainfall measurements, but, in order to take full advantage of this technology, the data must be readily accessible and in a form easy to comprehend. Unfortunately, this is not the case for most weather radar facilities. Typically, raw radar data are recorded on computer-compatible magnetic tapes as numbers (usually as binary numbers) which mean nothing to the user who is interested in rainfall rate or amount. The data must therefore be transformed into a usable format; this becomes a question of data management.

Weather radars, such as the Alberta Research Council radars near Red Deer, provide a lot of useful data about the three-dimensional structure of precipitation. Two radars can obtain reflectivity measurements: (1) S-band 10 cm and (2) C-band 5 cm. The S-band radar scans in a spiral with a circular beam of 1.15 degrees and data bins of approximately 1 km^3 volume at a 40 km range (Leung, 1977). The C-band radar also scans in a spiral with data collected at 1.5 degrees steps in elevation. The information needed to determine precipitation falling to the surface comes from frequent observations at low elevations (about 1 degree elevation for the S-band radar, and 1.5 degrees for the C-band radar). As an approximation (without taking into account the earth curvature), at 150 km, this is equivalent to a height of about 2.6 and 3.9 km, respectively for the two radars. The various steps required to transform these data into a simple and useful form are shown schematically in figure 8.

The received signals are first recorded on computer-compatible magnetic tape (2400 ft, 800 bpi). Next, the electrical calibrations and the radar equation are used to convert the raw digital data values into received powers, or equivalent radar reflectivity factors, or both. The data are then in units ready for use by radar meteorologists. To make the radar data easy to use, it is important that the above be carried out quickly and automatically, without burden to the user. At ASD, the procedure is to store calibrations and radar constants appropriate for each day on computer files. This allows access to the radar data to a user who is unfamiliar with the radar computer system, without him becoming involved with the radar computer log books or calculations of radar constants. In fact, the data are automatically converted to values of received power or reflectivity at the time the digital data are first examined. The radar reflectivities are recorded automatically at Penhold (near Red Deer) on computer-compatible tapes.

The amount of data stored on a computer tape is a function of the storm size and duration. For example, a single scan, at approximately the same elevation for the full coverage of the radar, results in over 50 000 values being collected every 1.5 minutes (or over two million values in an hour). In practice, the number of values recorded is much less, because the storm usually covers a small portion of the total area covered by the radar. From past experience, a tape may contain just a few hours of radar data (on very active storm days), or the entire day (with less active storms or from isolated ones). The tapes are transported to Edmonton within a day (for specific requested days), or within a few days when convenient. Because they are the only copies of original radar data, a user copy is made on request. Copying usually requires a few hours, depending on the number of tapes involved.

At this stage the intended application of the radar data determines the direction of computer software development. In the present study, maximum accumulated rainfall amounts in a given area are needed for various time durations. At this stage of data management, millions of data values of reflectivity are recorded by the ARC radar for a 625 km² area (25 km by 25 km is a typical slice of radar data). Storage considerations become critical as large volumes of data may be generated from a single rainstorm. For example, heavy rainstorms in Alberta may last many hours, or even days, and the radar collects information continuously over a 150 km range (one value for approximately each kilometre), for every degree up to 360 degrees in azimuth, and for up to 20 degrees in elevation. Thus, the data need to be compacted for easier data management and manipulation.

Two computer software packages have been developed to facilitate storage compaction in obtaining maximum rainfall amounts for specific durations in a selected area. The first package uses the ASD-VAX system while the second package uses the ARC-VAX system. Both systems are interconnected, allowing transfer of data and computer software to either system. The ARC-VAX package is adaptable to the Amdahl Computer facility at the University of Alberta. In fact, all the computer software in the ARC-VAX package (except the plotting routines) has been tested on the Amdahl system. The main difference between the two packages appears in the final graphs produced. The advantage of having the different packages available on the systems is that the user can still obtain a product even though one of the systems may be inoperative. Both software systems use a common tapedrive to read the radar data. The two packages are described next, together with the software programs used.

ARC-VAX computer software package

The first component of software development is to obtain radar information for a specific location and elevation (instead of the various elevations up to 8 or 20 degrees for the S-band, and up to 6 degrees for the C-band) that are stored on the magnetic tape. The resulting format can be modified through a version of a software routine called FOUR. This program extracts the needed information from an extremely large data base to a data file which is still relatively large, but workable in terms of storage. In the modified FOUR program, the user needs to select the specific location(s) (areas from a few to several thousand square kilometres). As a rule of thumb, areas up to 1000 km² are practical for rapid computer processing. It is also necessary to identify the time period desired, to minimize the time required in reading the radar data tape(s). The FOUR program produces a sequential file of unknown size depending on available data for the time required and contains: (1) the azimuth angle; (2) the bin number (equivalent to the range from the center of the radar); (3) the time to the nearest second; and (4) reflectivity. Concatenation of radar data from several tapes can be easily carried out by re-running the FOUR program.

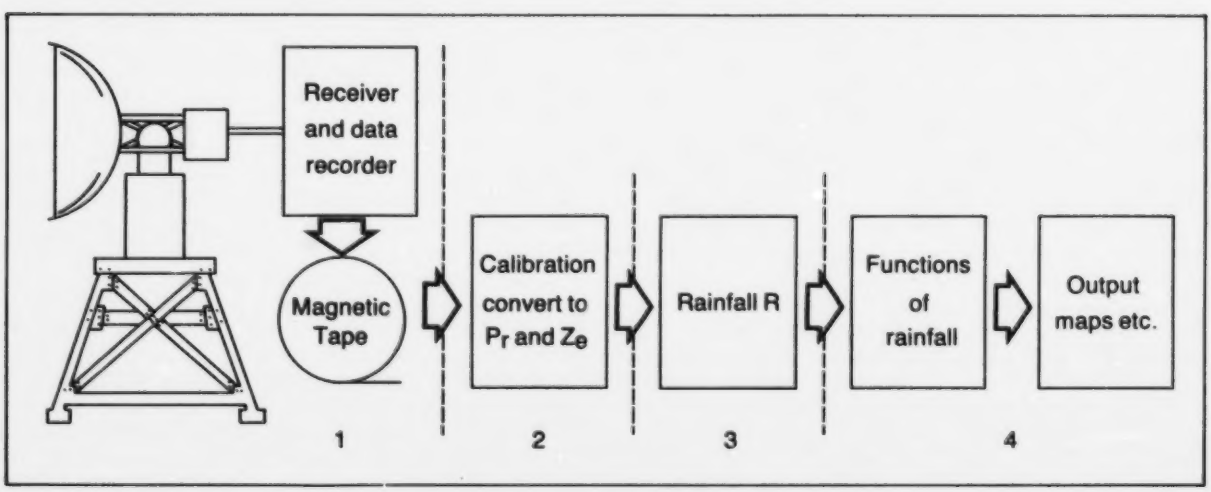

Figure 8. Schematic diagram for collection and storage of radar data (Barge and Humphries, 1978).

The resulting computer file from FOUR is next transferred to the ARC-VAX computer where a software package with command files has been developed to perform the necessary computations and plots to produce a final product. The command files enable a user to operate the computer package almost automatically.

In estimating the maximum rainfall amount for a given duration, it is first desirable to obtain the time distribution of the dBZ reflectivities for each bin. The output resulting from the FOUR program does not readily give this distribution. The time distribution is obtained in the software package by restructuring the data file so that, for each bin, the values of the reflectivities are sequentially ordered by time; this is accomplished by sorting the data file for bin number and time. Next, the computer package creates a sequence of reflectivities for each minute of the duration of the storm (with linear interpolation for values between recorded observations in dBZ reflectivities), resulting in a time distribution of reflectivities for each bin. The time distribution of reflectivities is next converted to rainfall rate by the Z-R relationship, with the user having the option of providing the A and b constants or using the default values ($A = 168$ and $b = 1.72$). This results in a time distribution of one-minute rainfall amounts for each bin. Next, each time distribution of rainfall amount is computer searched to obtain the maximum amount for the specified duration. Nine different durations (5, 10, 15, 30 minutes, 1, 2, 6, 12, and 24 hours) are programmed.

The results are saved in a permanent file, and contain, for each specified bin (range and azimuth), the maximum rainfall amount which occurred in any 5-minute duration during the storm, any 10-minute duration, and so on. For storms lasting less than a given duration (for example, 6 hours) the results for longer durations will have the same numerical value as for the total duration of the storm. The permanent file now contains the desired numerical values of rainfall amounts.

The user may want to examine a large area and it is not efficient to hand-plot hundreds or thousands of numerical values. Thus, contouring and plotting routines are utilized for more rapid computer production. Two computer programs are used: (1) GEOPLTR and (2) SURFACE II. The GEOPLTR is an interactive computer package for the production of plotted maps of areally distributed data within Alberta (developed by the Alberta Research Council Groundwater Department). The data locations must be designated in township-range-meridian, latitude-longitude, and azimuth-range coordinates. This package provides a capability for plotting observations for the entire province or selected areas on various user-selected map scales. The user needs to define the area of interest, which should be similar to the area selected in extracting the radar data. Theoretically, the user can choose whatever map scale is desired; however, practically, only a few (1:50 000, 1:125 000, 1:250 000 or 1:500 000) are commonly used with geographic or topographic maps. A command file (HYDRO) was also developed for using the GEOPLTR computer package, thus limiting the extensive interaction usually required with the package and making the system more automated for routine production. The GEOPLTR package provides the township-range overlay and the plots of locations and values.

The second package invoked in the command file is the SURFACE II package, which provides contoured observations. This package is also an interactive one, giving the user numerous alternatives. For routine production, the contour levels were selected at 5 mm increments in the command file. Any increment can be selected and easily changed at the discretion of the user. The SURFACE II package also offers the user numerous choices in the production of various smoothing techniques. Minimum smoothing (equivalent to the five-point formula), has been used because it is desirable to obtain a maximum contour level in the production of maps. The command file is also interactive, thus minimizing the number of decisions the user needs to make in operating the package, as the user should be more interested in the final results than in spending time answering routine questions.

ASD-VAX computer software package

As in the previous package, the ASD-VAX package requires decisions about area and time by the user. It does differ in three respects. First, the reflectivity is considered to be the same during the 1.5 minute scan, with no interpolation between consecutive scans. This produces only a slightly higher value in the total rainfall amount. (This can be shown through computations and is also observed by comparing results.) Second, a maximum area of about 625 km² can be selected at any one pass, in fixed 25 degree azimuth intervals, starting with 0 degrees, and in fixed 25 bin range intervals. Third, the final map is produced on a fixed scale of 1:500 000 (a scale used most frequently in ASD), and produced on a color printer. Various colors (up to 7 different ones) can be selected by the user to indicate specific rainfall amounts. The ASD-VAX package can also be used to quickly provide a map of areas exceeding specified rainfall amounts.

Case studies

Three cases were examined using the computer software developed in this study. The three rainstorms examined occurred on: (a) 5 July 1984, (b) 24 June 1983, and (c) 29 June 1982. The first case is the 5 July 1984 rainstorm which occurred over the city of Edmonton and produced extensive flooding at various locations along its path. Because the storm occurred over Edmonton where a large number of tipping-buckets are operated by the City, it provided an opportunity to compare radar observations with ground measurements. The Z-R relationship obtained from radar observations and rainfall measurements from the 5 July 1984 rainstorm was shown earlier in figure 6.

Three Z-R relationships were investigated for this storm: (a) the Marshall-Palmer (figure 9), (b) the Hood (figure 10), and (c) the Wojtiw (figure 11). Maps for the 5-minute durations (figures 9 to 11) are presented here because they provide the strictest time requirements (in available data) for comparison of radar observations with ground measurements.

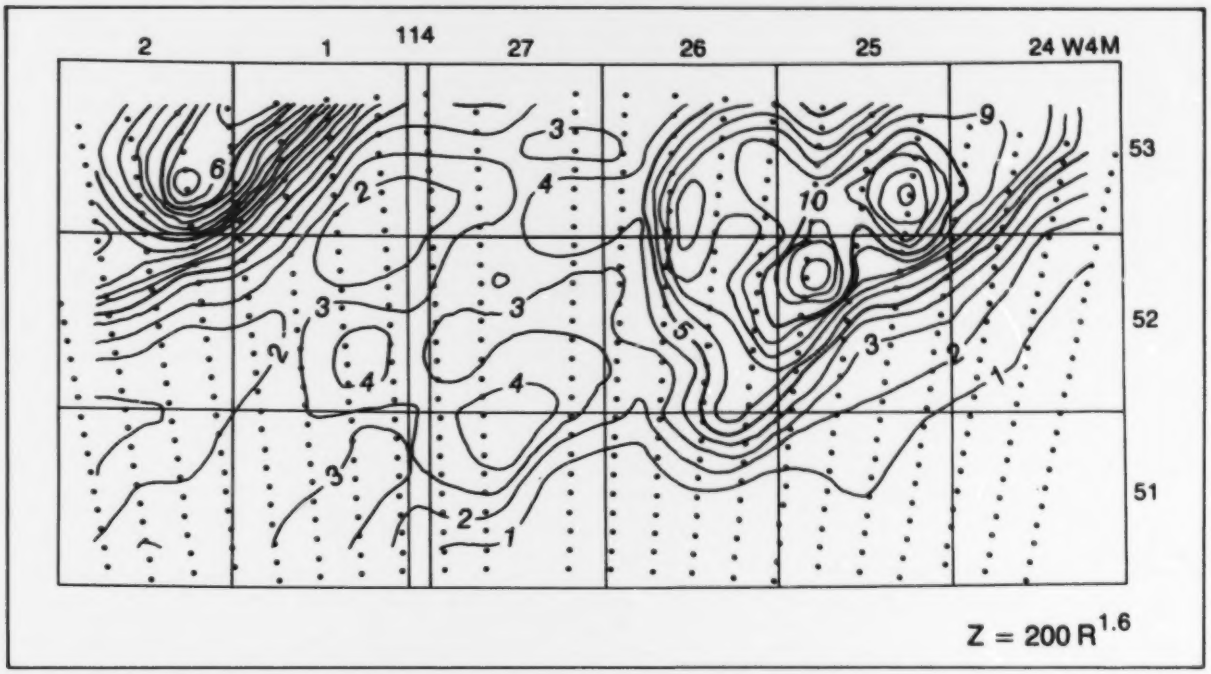

Figure 9. Map of maximum rainfall (mm) according to the Marshall-Palmer relationship for 5-minute duration for the 5 July 1984 rainstorm (ARC-VAX package).

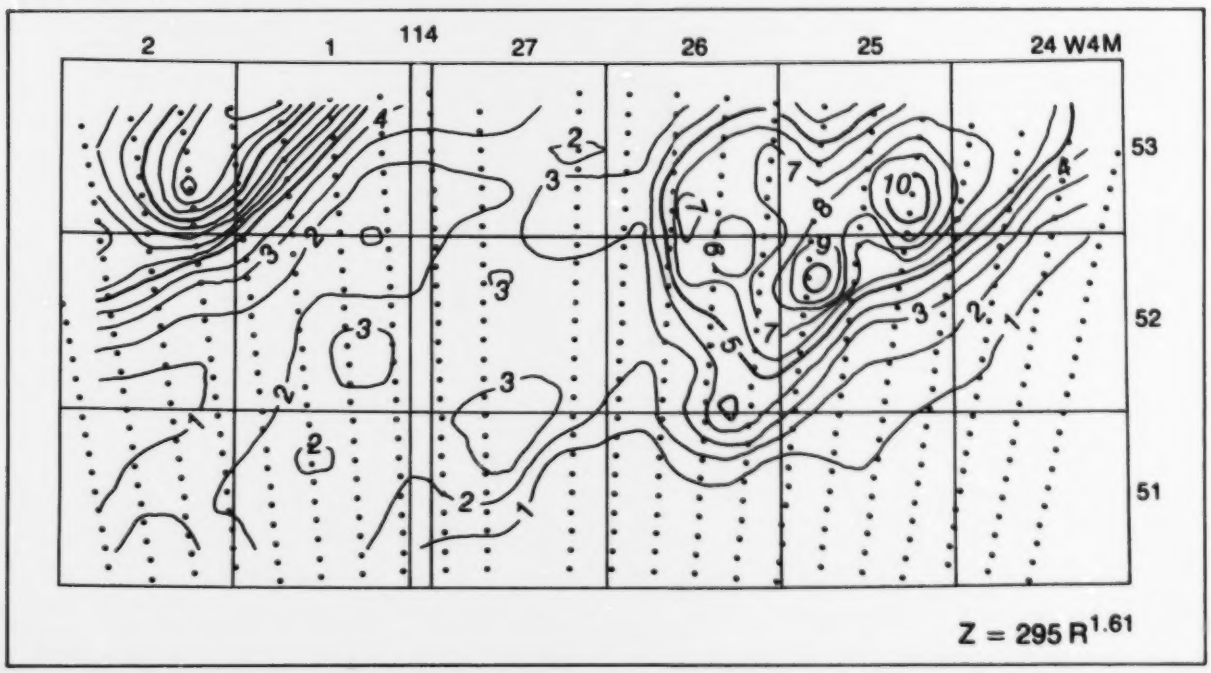

Figure 10. Map of maximum rainfall (mm) according to the Hood relationship for 5-minute duration for the 5 July 1984 rainstorm (ARC-VAX package).

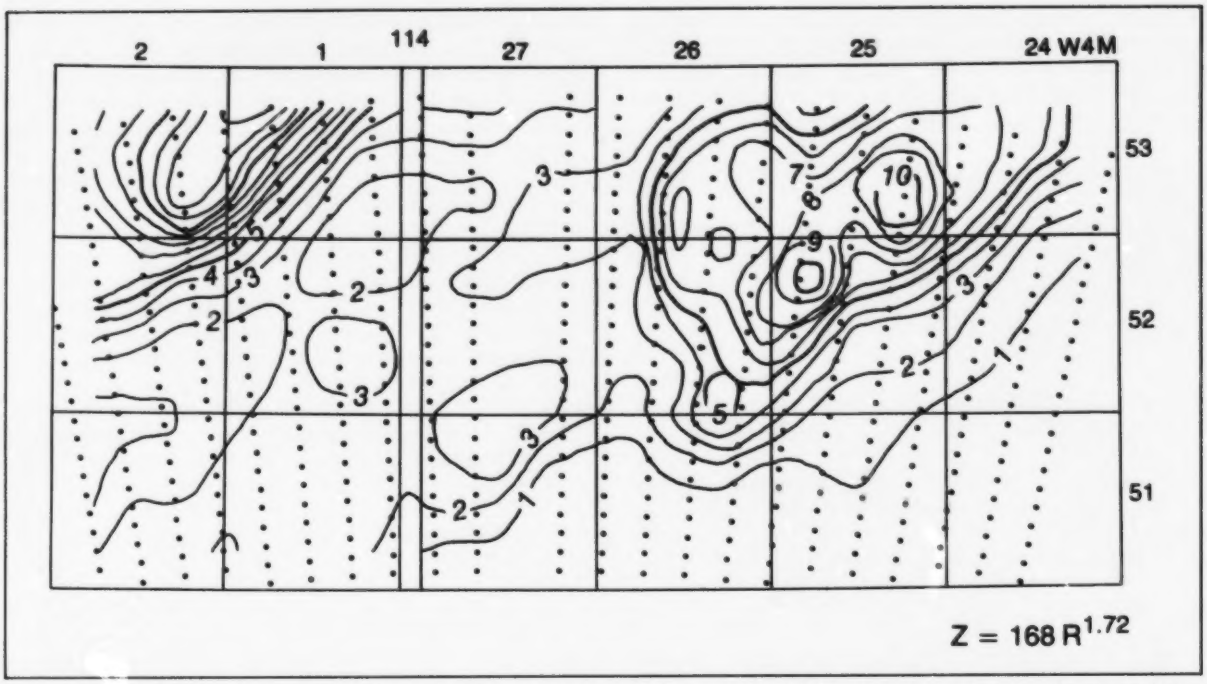

Figure 11. Map of maximum rainfall (mm) according to the Wojtiw relationship for 5-minute duration for the 5 July 1984 rainstorm (ARC-VAX package).

The Marshall-Palmer relationship (figure 9) shows overall higher rainfall amounts compared to point-rainfall measurements taken from ground observations. It needs to be pointed out that the radar bin typically covers more than a 1 km² area (at the range of the City of Edmonton) and that the radar reflectivity value given for this area is an average value, while the raingauge value is a point measurement. Hence, the radar observations represent a much larger area than that being sampled by one raingauge. The Hood relationship (figure 10) yields values that are closer to those obtained by the ground measurements but are lower than those obtained by the Marshall-Palmer relationship. Figure 11 shows the results obtained using the Wojtiw relationship; these amounts correspond closer to the ground observations. Comparing the 5-minute 1-in-25 year event (figure 12) with the results obtained from the three Z-R relationships shows that one main area exceeded the 1-in-25 year event in the 5 July 1984 storm. A similar comparison can be made for the 24-hr 1-in-25 year event (figure 13) using 24-hour intensity-duration values. For all three relationships, the same area exceeded the 1-in-25 year event, thus indicating that, in general terms, any of the three relationships could have been used successfully for this hydrological application. Although the scale used in figures 9 to 11 is 1:250 000, the computer software can also be used to produce maps on a 1:100 000 scale. The maximum 5-minute duration rainfall amounts ob-

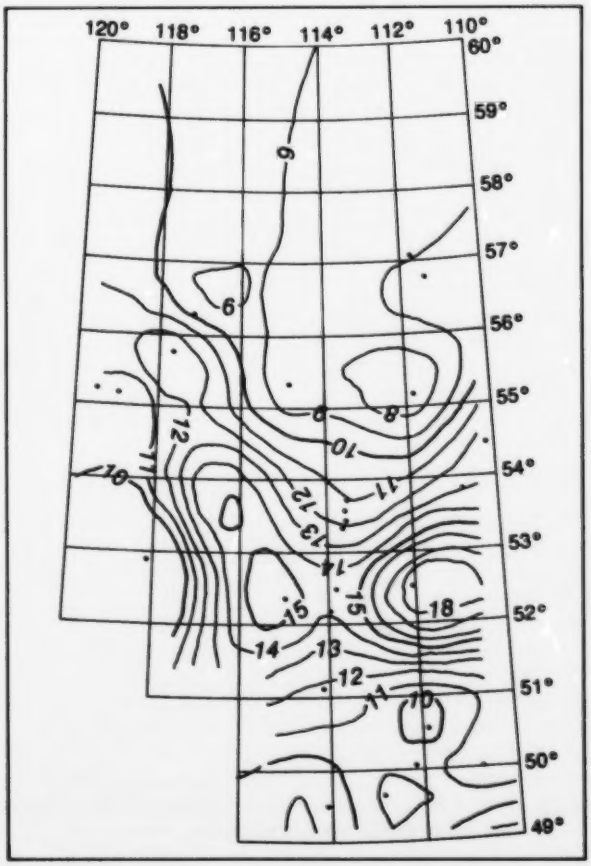

Figure 12. Spatial distribution of the 5-minute 1-in-25 year rainfall amount (mm) for Alberta.

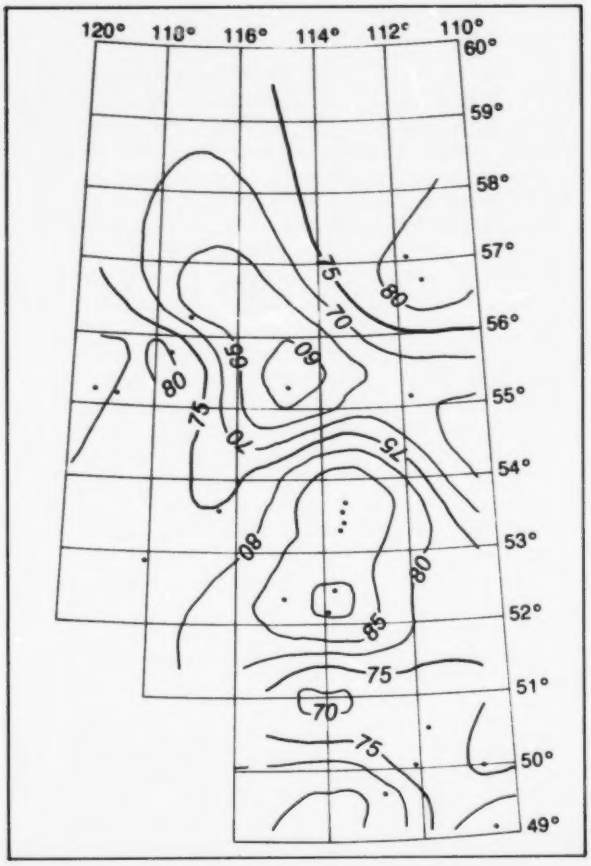

Figure 13. Spatial distribution of the 24-hour 1-in-25 year rainfall amount (mm) for Alberta.

tained from the ground measurements are shown in figure 14.

The second case examined occurred on 24 June 1983 in an area near Stettler. A cold low system that occurred between 23 to 25 June in central Alberta produced a variety of rainfall intensities during the storm period. For the location selected, no tipping-bucket data were available; however the daily rainfall amounts collected by the ASD network generally agreed with three radar estimates.

The third example for which the computer software was tested was the 30 June 1982 rainstorm. This storm was selected to test the computer software for C-band radar data, azimuth, and range. A small area near Camrose was selected for this case, with about five hours of radar data analyzed by the computer software. The results obtained from the radar data are comparable to the sparse nonrecording rainfall information that is available.

The comparisons of maximum rainfall amounts derived from radar data for the three different Z-R relationships to those recorded by surface raingauges, for the three cases combined, are shown in figure 15. The solid line in figure 15 is the one-to-one line representing perfect agreement between any Z-R relationship and the corresponding surface raingauge measure-

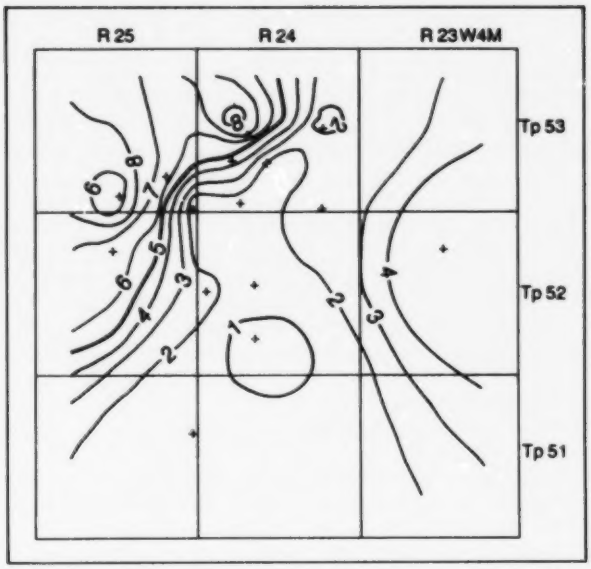

Figure 14. Map of 5-minute surface maximum rainfall (mm) from the 5 July 1984 rainstorm.

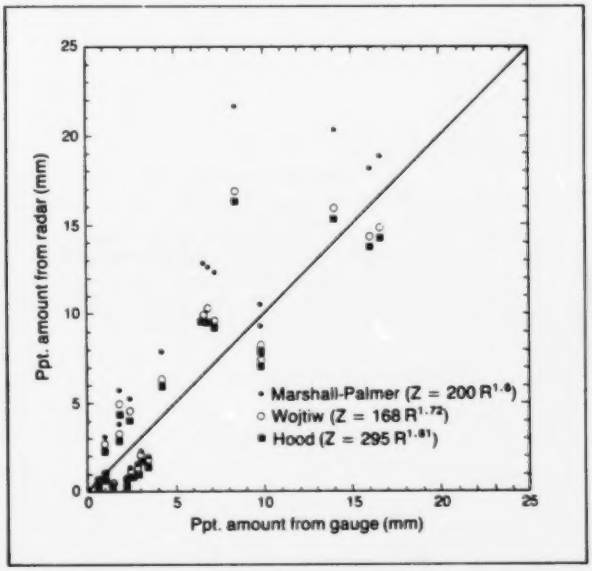

Figure 15. Comparison between radar and surface raingauge estimates of maximum rainfall for the three Z-R relationships.

ment. Deviation from this line, either up or down, indicates a difference between the Z-R estimate and the ground measurements. The results for the three relationships show that, overall, the Wojtiw Z-R relationship gives better estimates of maximum rainfall amounts, compared to ground measurements for Alberta rainstorms, than do either of the other two relationships (Marshall-Palmer or Hood). The results are particularly good for the higher rainfall amounts (greater than 5 mm).

Summary and conclusions

Two computer software packages have been developed in this study to produce maps of radar-derived maximum rainfall amounts for nine different durations ranging from 5 minutes to 24 hours. Although the computer packages require minimum user interaction, they offer a variety of possible selections. The user needs to identify the location for which maximum rainfall maps are desired, as well as the approximate duration of the storms. The computer software also offers the user the choice of selecting the Z-R relationship, the map scale, and/or the contour interval. (In the computer package, default values are supplied for these quantities based on the best practical application.)

Several conclusions were reached in the course of this study:

1. Weather radar data can be made readily available to hydrologists to provide more objective assessments of rainfall from severe rainstorms. Weather radar data can provide information on the spatial distribution of maximum rainfall amounts, leading to better insight regarding areas where the water exceeded conveyance criteria (1-in-25 year event).
2. Weather radar data can provide a much larger number of estimates of rainfall amounts than is presently produced by conventional networks in Alberta.
3. An empirical Z-R relationship (Wojtiw) (in which $A = 168$ and $b = 1.72$), developed in this study, has proven to yield a better correspondence between radar and ground observations for Alberta rainstorms (in the limited number of cases tested) than either the Marshall-Palmer or Hood relationships. This Z-R relationship is recommended for tentative use in Alberta, since it is the first developed specifically for Alberta rainstorms. It is also recommended that work on the Z-R relationship continue in Alberta.
4. Maps of maximum rainfall amounts for nine different durations can be produced in a relatively short time period (within a few days). Other durations can be created easily with minor changes in programming.
5. The computer software can easily handle analysis of areas of about 500 km^2 without exceeding storage capabilities or requiring extensive computer time. (Originally, it was believed that such large areas could not be handled.)
6. The computer software package can be easily automated to minimize user interaction, with the user required to specify only desired criteria (for example, area of interest, time and date of rainstorm).

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